Renewable and Sustainable Energy Reviews 24 (2013) 544–556

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Geographical Information Systems (GIS) and Multi-Criteria Decision Making (MCDM) methods for the evaluation of solar farms locations: Case study in south-eastern Spain

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ARTICLE INFO

Article history:
Received 21 November 2011
Received in revised form
2 March 2013
Accepted 4 March 2013
Available online 27 April 2013

Keywords:
Optimization locations
Photovoltaic plants
Geographic Information Systems (GIS)
Multi-Criteria Decision Making (MCDM)
Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)
Analytic Hierarchy Process (AHP)

ABSTRACT

This paper is based on the combination of a Geographic Information System (GIS) and tools or multi-criteria decision making (MCDM) methods in order to obtain the evaluation of the optimal placement of photovoltaic solar power plants in the area of Cartagena (Region of Murcia), in southeast Spain.

The combination GIS–MCDM generates an excellent analysis tool that allows for the creation of an extensive cartographic and alphanumeric database that will later be used by multi-criteria methodologies to simplify problems to solve and promote the use of multiple criteria.

In GIS two types of criteria will be reflected: constraints or restrictive criteria, and weighting criteria or factors. Constraints or restrictive criteria will make it possible to reduce the area of study by discarding those areas that prevent the implementation of renewable energy plants. These criteria will be obtained from the legislation (planning regulations, protected areas, road networks, railways, waterways, mountains, etc). Weighting criteria or factors will be those which, according to the objective to be reached, influence the ability to solve a concrete alternative. The choice of such criteria is marked by the influence presented to the overall goal; in this case they will be location, geomorphological, environmental and climatic criteria.

Through the use of MCDM the criteria or factors mentioned will be weighted in order to evaluate potential sites to locate a solar plant. Analysis and calculation of the weights of these factors will be conducted using Analytic Hierarchy Process (AHP). The assessment of the alternatives according to their degree of adequacy is carried out through the TOPSIS method (Technique for Order Preference by Similarity to Ideal Solution).

Contents

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1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.03.019

1. Introduction

1.1. Renewable energy in Spain

The current economic situation, the rising global energy demand and rational use of the available resources are driving the search for energy alternatives to meet the needs of the present without compromising those of future generations; the goal of sustainable development is enabling advances in the research into new strategies to optimize the resources and technologies currently available. To that end, several studies have been developed in this area [1].

In Spain, the necessary growth containment of greenhouse gas emissions set by the Kyoto Protocol [2] and, the compliance of the objective stated in the White Book of the European Union [3], were the main reasons why the so-called Plan of Promotion of the Renewable Energies (PLAFER) [4] was created in order to encourage the use of renewable energy. Among the different types of renewable energy, photovoltaic solar energy is proving reliable and, although it has not reached sufficient maturity, significant efforts are being made in technology research pointing toward lower manufacturing costs and higher efficiencies [5,6].

According to the Global Market Outlook for Photovoltaics until 2016 report produced by the European Photovoltaic Industry Association (EPIA), although energy policies have reduced their expansion, Spain continues to be situated at the top as a producer of photovoltaic solar energy. In 2011 it stood in fourth place worldwide with respect to solar power installed, Fig. 1

Photovoltaic power values allocated by the Ministry of Industry, Tourism and Trade of the Government of Spain (MITyC) published in the annual report of 2010 of the Photovoltaic Industry Association (ASIF) indicate that the Region of Murcia is ranked fourth nationally, only exceeded by Castilla León, Andalusia, and Extremadura.

The high level of photovoltaic solar power generated in the Region of Murcia is because this region has one of the highest levels of potential or solar radiation in the country; specifically in the area of Cartagena the average annual global radiation in most of its territory exceeds 5.00 KW/m^2 day, [8].

1.2. Application of Multi-Criteria Decision Making methods (MCDM) in renewable energy

The purpose or ultimate goal of a Multi-Criteria Decision Making method is to investigate a number of alternatives in the light of multiple criteria and conflicting objectives [9].

One of the most popular MCDM is the Analytic Hierarchy Process—AHP [10], its main feature is that the decision problem is modeled using a hierarchy whose apex is the main objective of the problem and the possible alternatives to be evaluated are located at the base. In this paper, the AHP methodology will be used to determine the weight of the criteria or factors in our decision problem.

Another method commonly used is the Technique for Order Preference by Similarity to Ideal Solution TOPSIS [11], this method is currently used to identify solutions that are as close as possible to an ideal solution applying for it some measure of distance, and thus indicated solutions are called compromises. TOPSIS will be used to assess the carrying capacity that will fit the different locations to install solar photovoltaic power plants.

The application of MCDM has been conducted in many applications and disciplines, Ho [12] made a review of the applications of the AHP model integrated with other techniques. Below, some of the many examples of application of MCDM in the investigation of sources of renewable energy are mentioned.

Huang et al. [13] used various MCDM such as ELECTRE, AHP, TOPSIS, etc. to conduct an analysis of the energy system. In 1997, Georgopoulou et al. [14] studied the advantages and disadvantages of the implementation of renewable energy in the Greek islands using the ELECTRE III method. In Italy, Beccali et al. [15] used the multi-criteria decision system to assess the different energy alternatives. Haralambopoulos and Polatidis [16] applied PROMETHEE II to investigate and assess the exploitation of a geothermal energy source in the island of Chios (Greece). In 2004, Pohekar and Ramachandran [17] applied MCDM to energy planning. In southern Spain, in Andalusia, Terrados et al. [18] developed a combination of methodologies (including MCDM) for a renewable energy plan. More recently, Eunnyeong et al. [19] used the fuzzy AHP methodology to evaluate a renewable energy program. In the same year, Cavallaro [20] employed the Fuzzy TOPSIS approach for assessing thermal-energy storage in a concentrated solar power system.

1.3. GIS-based Multi-Criteria Decision Making methods

According to the National Center for Geographic Information and Analysis of the USA (NCGIA) a GIS can be defined as a hardware and software system, designed for the capture, storage, analysis, modeling and data presentation, spatially referenced, for the resolution of complex problems of planning and management.

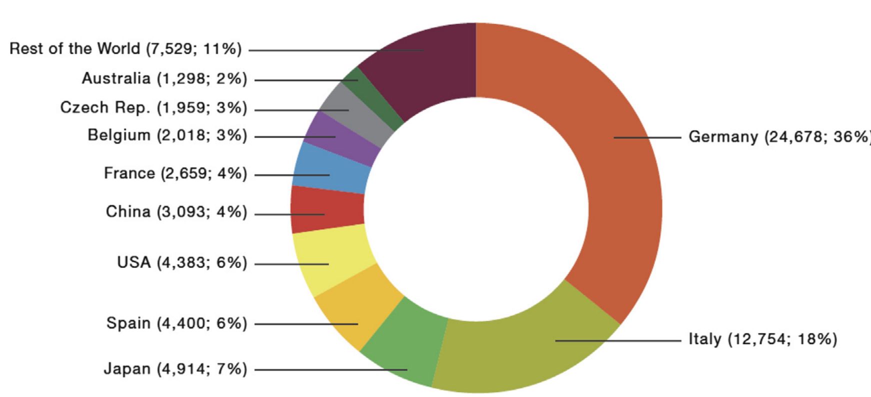

Fig.1. Global cumulative installed capacity share 2011 (MW, %) [7].

GIS are commonly used in various disciplines such as scientific research in its broadest concept; cartography; navigation; logistics; urban planning; etc.

The successful combination of GIS and technical decision support is that they are perfectly complementary tools. GIS offers the decision-maker or decision-maker group the possibility of carrying out the analysis, management, storage and visualization of all geospatial information. Based on such functions, the MCDM provide a range of techniques and procedures that allow to structure decision problems and evaluate the alternatives under study [21].

Since they were released, the GIS–MCDM have been used in numerous studies of territorial planning such as urban planning, urban infrastructure, etc [22–25].

At present, the combination of GIS–MCDM is spreading to applications relating to energy. In the state of Georgia (USA), Defne et al. [26] evaluated the possibility of installing tidal power plants by combining GIS and multiple criteria. In Oman, Charabi and Gastli [27] studied the suitability of installing solar photovoltaic power plants by mixing GIS and multi-criteria fuzzy methodology.

In Europe, energy studies have also begun in the region of Tuscany (Italy), Mari et al. [28] used GIS and MCDM linked to an interactive website to plan the installation of wind farms.

In the region of Granada in the south of Spain [29], due to the peak of the photovoltaic solar energy, carried out research into the choice (combining GIS with AHP) of the best location for solar photovoltaic installations connected to the power supply.

In this paper the combination of GIS and MCDM (AHP and TOPSIS) will be used to obtain the evaluation of the optimal placement of photovoltaic solar power plants in the area of Cartagena, Spain.

The rest of the paper is organized as follows: In Section 2, the GIS is considered and is related with the problem in question. The suggested methodology is described in Section 3. In Section 4 the GIS–MCDM methodology is applied to the location of photovoltaic energy installations. Finally, in Section 5, data results and discussion are presented and the most important conclusions of the work are detailed.

2. Geographic Information System (GIS)

GIS can be defined as tools for consulting, analyzing and editing data, maps and spacial information in general. They are computer systems (hardware and software) used for analysis, consulting, developing, manipulating, storing, or in short, for handling geographic information. Therefore, GIS are systems that work with geographic information databases.

On a digital map, we have a database associated with it, in which we can obtain the geographic coordinates of each point. This means that it is possible to search in both directions, obtaining information on the map or performing the search directly from the database.

There are two types of GIS representation, by raster data or by vector data. Raster models are represented by a mesh or grid of rectangles, all with the same size. Each element is called a pixel or cell and has its information and geographic location assigned to it. In a vector model, the geographic features in GIS are expressed as vectors, maintaining the geometric features of the figures. They are used to define boundaries and therefore spatial geometries. The vector elements have associated information in the database. The vector geometric elements used are: dots, lines and polygons.

It is also clear that GIS present some difficulties to become the general tool for solving all types of spatial problems. These difficulties arise from two sources: the deficiencies in the analytical methods usually integrated into a GIS and the tools that usually constitute a GIS are too generic and unspecialized [30].

Today, there are powerful GIS on the market; several alternatives were studied for the development of the current project, but eventually gvSIG was chosen to be used. The gvSIG software has a wide range of features that were necessary for developing the project. The fact that the software is free was also a criterion for the choice. It was promoted by the Generalidad Valenciana, but is now embraced by a large group of companies, administrations and universities that come under the gvSIG association (Iver, Prodevelop, Software Colaborativo, Creativa, Conselleria de Infraestructuras y Transportes).

The gvSIG software can work with both raster and vector information. It is also possible to access server maps that comply with OGC specifications. The ability to access services such as WMS (Web Map Service); WFS (Web Feature Service); WCS (Web Coverage Service); Catalog Service; and Nomenclator Service, is a great advantage as compared to many GIS.

A GIS organizes the geographic data so that a person reading a map can select the necessary data for a particular project or task. A thematic map with a table of contents allows the reader to add layers of information to a basemap of real world locations (Fig. 2)

This illustrates the major potential it has for manipulating geographic information via the GIS to nurture a Decision Support System (DSS). When DSS apply to environmental or spatial planning, they require a large amount of spatial information. GIS

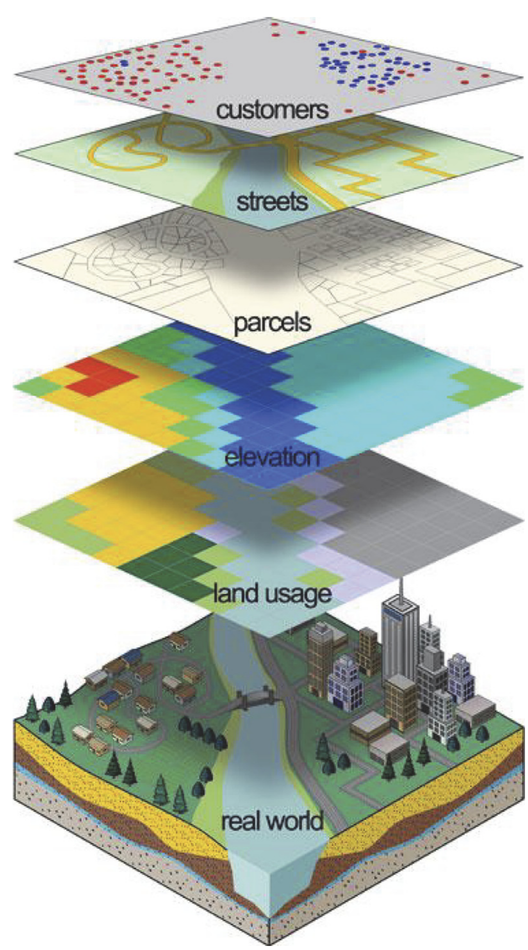

Fig. 2. GIS layers model. www.gembc.ca.

are essential for this task, and can be used to develop highly flexible DSS that can be applied to similar problems.

Applying GIS allows one to operate alone or together, with the most diverse number of variables, considered spatially. This form of geographic information management allows multi-criteria analysis, given the possibility to combine and simultaneously evaluate the criteria (the basis for making decisions) with their factors (aspects that enhance or reduce them) through the use of their attributes (variables) within a certain range of decision rules and assessment [31].

This paper presents a methodology for solving the problem of optimal localization of photovoltaic installations connected to the electricity network. It can be considered as a practical application of the facilities location problem widely discussed in the bibliography [32].

3. Multi-Criteria Decision Making methods (MCDM)

Ever since the world has existed, people have found themselves involved in taking decisions that concern their daily life. For many years researchers have been interested in the analysis of how the human carries out this task. In this sense, a modeling of the context in which we are to move is necessary, i.e., in such a way that it simplifies (represents) the real system, and with the condition that it is readily understood and is easy to implement. Thus, we study the alternatives that we can choose, as well as the criteria on which said alternatives are to be evaluated. This, which at first sight seems to be simple, forms part of the whole discipline that is called Multi-Criteria Decision Making (MCDM) [33,11,34].

MCDM is a procedure that consists in finding the best alternative among a set of feasible alternatives. A MCDM problem with m alternatives and n criteria can be expressed in matrix format as follows Fig. 3 where $A_1, A_2, \cdots, A_m$ are feasible alternatives; $C_1, C_2, \cdots, C_n$ are evaluation criteria; z_{ij} is the performance value of alternative A_i under criterion C_j; and w_j is the weight of criterion C_j.

To properly determine the weight of each criterion or factor involved in the final outcome of the resulting layers, the Analytic Hierarchy Process AHP method [35], proposed by Saaty in 1980 has been used within the MCDM. It is a pair-wise comparison procedure of the criteria that is based on a square matrix in which the number of rows and columns is defined by the number of criteria to weigh.

The Analytic Hierarchy method has been widely applied in solving a variety of problems, among which are the applications related to energy planning and the carrying capacity of renewable energy facilities [36,37].

On the other hand, to evaluate diverse alternatives according to their suitability, the TOPSIS method will be used (Technique for Order Preference by Similarity to Ideal Solution). This method bases its operation in the calculation of the distances to the ideal point and the anti-ideal point. This methodology was chosen because it does not require an assessment by the expert for each of the alternatives; they can be evaluated directly from the database provided by the GIS assessment of each criterion for each alternative. For the technique and application of GIS-based ideal point see [30].

$$
\begin{array}{cc}
 & \begin{array}{cccc} w_1 & w_2 & \cdots & w_n \\ C_1 & C_2 & \cdots & C_n \end{array} \\
M = \begin{pmatrix} A_1 \\ A_2 \\ \vdots \\ A_m \end{pmatrix} & \begin{pmatrix} z_{11} & z_{12} & \cdots & z_{1n} \\ z_{21} & z_{22} & \cdots & z_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ z_{m1} & z_{m2} & \cdots & z_{mn} \end{pmatrix}
\end{array}
$$

Fig. 3. Decision matrix.

Table 1
Saaty's preferences in the pair-wise comparison process.

Verbal judgements of preferences between alternative *i* and alternative *j*	Numerical rating
A_i is equally important to A_j	1
A_i is slightly more important than A_j	3
A_i is strongly more important than A_j	5
A_i is very strongly more important than A_j	7
A_i is extremely more important than A_j	9
Intermediate values	2, 4, 6, 8

3.1. Analytical Hierarchy Process (AHP)

The AHP methodology [35] has been accepted by the international scientific community as a robust and flexible multi-criteria decision-making tool for dealing with complex decision problems. Basically, AHP has three underlying concepts: structuring the complex decision problem as a hierarchy of goal, criteria and alternatives, pair-wise comparison of elements at each level of the hierarchy with respect to each criterion on the preceding level, and finally vertically synthesizing the judgements over the different levels of the hierarchy.

AHP is based on a firm theoretical foundation. The basic theory of AHP may be simplified as follows: we assume that we have n different and independent alternatives ($A_1, A_2, \cdots, A_n$) and that they have the weights ($w_1, w_2, \cdots, w_n$), respectively. The decision-maker does not know the values of w_i, $i = 1, 2, \cdots, n$ in advance, but he/she is capable of making a pair-wise comparison between the different alternatives. Also, we assume that the quantified judgements provided by the decision-maker on pairs of alternatives (A_i, A_j) are represented in an nxn matrix as follows:

$$
\begin{array}{ll}
 & \begin{array}{cccc} A_1 & A_2 & \cdots & A_n \end{array} \\
A = \begin{array}{c} A_1 \\ A_2 \\ \cdot \\ \cdot \\ A_n \end{array} & \begin{bmatrix} a_{11} & a_{12} & \ldots & a_{1n} \\ a_{21} & a_{22} & \ldots & a_{2n} \\ \cdot & \cdot & \ldots & \cdot \\ \cdot & \cdot & \ldots & \cdot \\ a_{n1} & a_{n2} & \ldots & a_{nn} \end{bmatrix}
\end{array} \tag{1}
$$

The values assigned to a_{ij} according to the Saaty scale [35] are usually in the interval of 1–9 or their reciprocals. Table 1 presents Saaty's scale of preferences in the pair-wise comparison process.

Although the AHP methodology allows for the evaluation and analysis of alternatives and thus the final result of the decision problems posed, this article will be focused on the initial steps that will establish the weights of the criteria because the analysis and evaluation of alternatives will be developed with the TOPSIS method.

3.2. TOPSIS method

In MCDM, a number of alternatives have to be evaluated and compared using several criteria. The aim of MCDM is to provide support to the decision-maker in the process of making the choice between alternatives. In this way, practical problems are often characterized by several conflicting criteria, and there may be no solution which satisfies all criteria simultaneously. Thus, the solution is a compromise solution according to the decision-maker's preferences. In this sense, TOPSIS is based on the concept that the chosen alternative should have the shortest distance from the Positive Ideal Solution (PIS) and the farthest from the Negative Ideal Solution (NIS). The final ranking is obtained by means of the closeness index.

The TOPSIS procedure consists of the following steps (Fig. 4).

4. GIS–MCDM methodology in the location of photovoltaic energy installations

The research was performed in two phases, the first focused on the development of a method by which people could obtain the suitable areas for the location of solar farms in the investigated area. Subsequently, suitable plots were evaluated via MCDM, more specifically, the AHP method was used to determine the importance of the different criteria used in the process and then TOPSIS was used to evaluate the alternatives. This whole process would eventually lead to achieving the most favorable area for the installation of solar photovoltaic plants.

The necessary information should be obtained to begin the data processing: the layers to work with in gvSIG, and obtaining the legal related framework. The layers should contain all possible information that we could relate to the establishment of an installation of considerable size in an outdoor space and which could prove to be a visual and environmental impact. Any administrative, technical or environmental aspect that would limit the construction of a facility of this size should be taken into account to give us a realistic view of the final result.

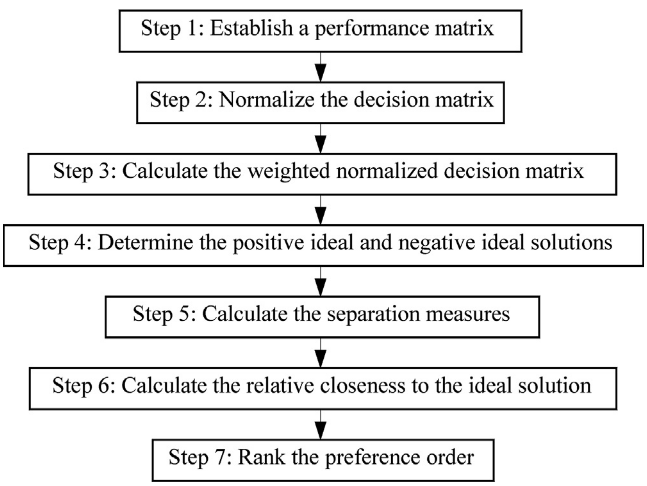

Fig. 4. TOPSIS method algorithm.

The government of the Region of Murcia offers the public a great deal of geographic information in GIS format through the SITMURCIA portals or CARTOMUR. This was the tool used for most of the layers. When searching for the layers, these must meet certain requirements:

- The layers should be in a format that gvSIG can process or, if gvSIG is unable to work with this format, the file format could be changed.
- Updated layers can be obtained, so that the information will be as realistic and up to date as possible.
- The current legal framework is available as is the applicable legislation in each case, whether at municipal, regional or state level.

In the multi-criteria evaluation field, the aim is the apex of the pyramid. In this paper, the aim is the selection of favorable location to place photovoltaic plants connected to the electricity network. Based on this aim, a decision rule appropriate to the problem, which also incorporates the criteria established, was chosen and structured. Barredo Cano and Gómez Delgado [31] propose the following flow chart for determining a model for resolving a spatial planning problem. This structure has been maintained for this paper (Fig. 5).

4.1. Phase I: determining suitable plots

The thematic layers that were used and their corresponding sources were as follows (all layers include information from across the Region of Murcia which is the limit of the studied area) (Table 2).

It was necessary to consider the current legislation for the process at hand. In most cases it was necessary to take legal restrictions into account to delimit the areas suitable for location of photovoltaic solar farms.

While in some cases it was necessary to resort to terrain criteria, the physical impossibility or simply the inadequacy of the land was a sufficiently restrictive criterion to eliminate certain areas in some cases. However, most come from the restrictions given by law, so an inventory of the legal framework had to be established with the current legislation.

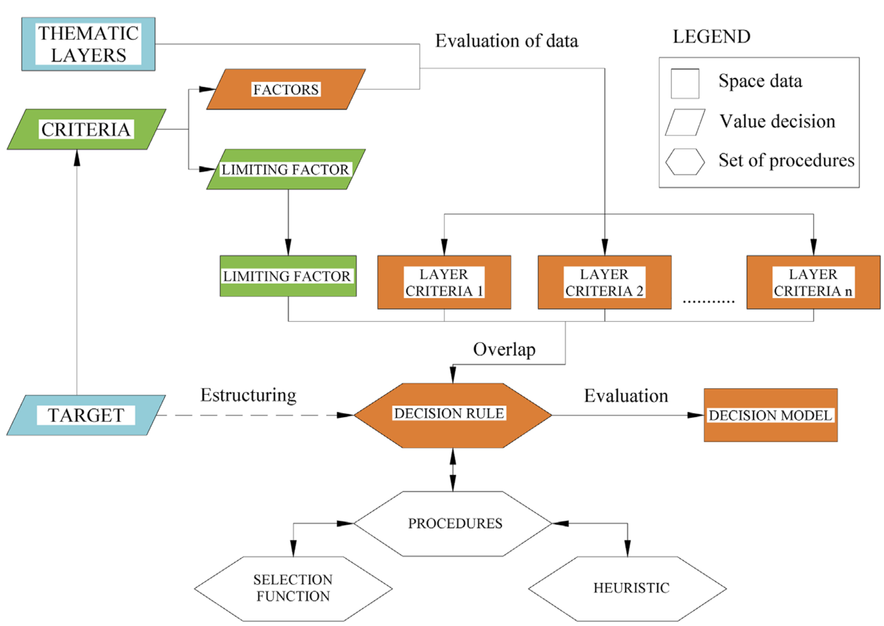

Fig. 5. Decision model for a territorial issue [31].

Table 2
Thematic layers used.

Layer	Supplier
Land classification	Consejería de Obras Públicas y Ordenación del Territorio, Unidad de Información Territorial de la Región de Murcia
Equipment and services (infrastructure, military zones and cattle trails)	
Cultural heritage	
Paleontological sites	
Archeological sites	
Watercourses and streams	
Areas of special protection for birds (ZEPAs)	Dirección General de Patrimonio Natural y Biodiversidad de la Región de Murcia
Community interest sites (LICs)	
Mountains	
Cadastral municipalities of Cartagena, Fuente Alamo, Torre Pacheco, La Unión and Murcia	Dirección General del Catastro. Ministerio de Economía y Hacienda
Agrological_Capacity of Comarca de Cartagena	
Orthophoto of Comarca de Cartagena	Plan Nacional de Ortofotografía Aérea (PNOA)
Field orientation and slope	Universidad Autónoma de Barcelona, del Atlas Climático Digital de la Península Ibérica
Potential solar radiation	
Average annual temperature	
Power lines of Comarca de Cartagena	Iberdrola Distribución Eléctrica, S.A.U

It is necessary to evaluate various environmental criteria, protected areas, visual impact, points of archeological and paleontological interest, and areas of difficult access such as hills or steep slopes [38].

In decision-making processes, taking these criteria into account when choosing the best area for the location of a facility can be observed [29], considering such criteria as limiting, so that in the areas in which a park or an area of special protection is defined, it will not be possible to install the photovoltaic plant.

Therefore, the main idea in this phase is to eliminate those areas of the zone which have impediments to the installing of a photovoltaic plant. The criteria studied were the following: Types of location, location Cataloguing, Communication lines, and Infrastructures such as Topography, Hydrology, Heritage and Protected Areas. Based on these criteria the decision was made for each of the aspects to be considered mentioned above, as areas unsuitable for the location of a solar farm.

On the other hand there are aspects that are not as clear, and although it is feasible to install solar farms in protected areas such as a Site of Community Importance (LIC), the location, and carrying out any construction or installation in an area of these characteristics would lead to the development of an environmental impact assessment, therefore this area would be considered as unsuitable as the location. Thus, taking a conservative approach such places would be eliminated [29].

From the initial layer of the municipalities, each of the restrictive layers involved were trimmed over time, as was the territory, and finally, the resulting areas were obtained, to eliminate unsuitable ones. The end result was a layer in which only suitable areas appear. The goal of this research is to assist in the selection of areas suitable for the localization of solar farms to enable as a last step, to select the plots contained in the layer of suitable areas. The maps used for each of the limiting criteria are those corresponding to Appendix A.

Once the restrictions had been established, the research into gvSIG layer treatment began. From this point onwards, the elimination of non-suitable surfaces began (Fig. 6).

A resulting layer was obtained with the suitable areas. The total area covered by these was of 270.78 km^2. The initial research on the acceptance capacity of generating facilities using photovoltaic solar panels gave us as a result that 25.50% of the studied area was safe for use (Fig. 7).

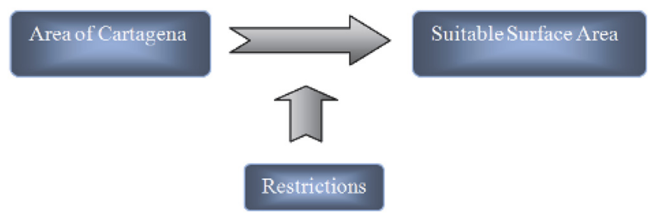

Fig. 6. Application of restrictions.

The process undertaken so far has resulted in the establishment of restrictions depending on the location, protected areas, infrastructures, etc. to eventually obtain those areas where it would be feasible to establish an installation with these characteristics. It is very useful to break down the land into lots as described by the land registry to establish the suitability for each individual plot. The initial idea is to take a suitable surface layer as a starting point, and then to make that area suitable for land registered plots.

The use of a new layer such as that in the land registry was useful for establishing two more restrictions:

- The plots that had already been built on are considered unsuitable
- The electricity generating facilities in this project are designed to be introduced into the electricity network hence generating a high energy level; therefore the minimum area required for the production of electricity with photovoltaic technology is fixed at 1000 m^2.

The layer with all the land register or cadastral information contains a total of 203,912 rural plots, each of which is a record in the database that has the following assigned information:

A filter was performed on the layer with the land register information on plots that had been built on as well as the plots that had an area of less than 1000 m^2. A total of 12,655 plots of the initial 203,912 met the two conditions, the resulting layer was named Plots. The next step was to select, from the 12,655 plots, which of them were located in suitable areas.

Having reached this point, the joint research on the information obtained from the land register commenced, i.e., the elimination of non-useful plots besides other areas of the land in

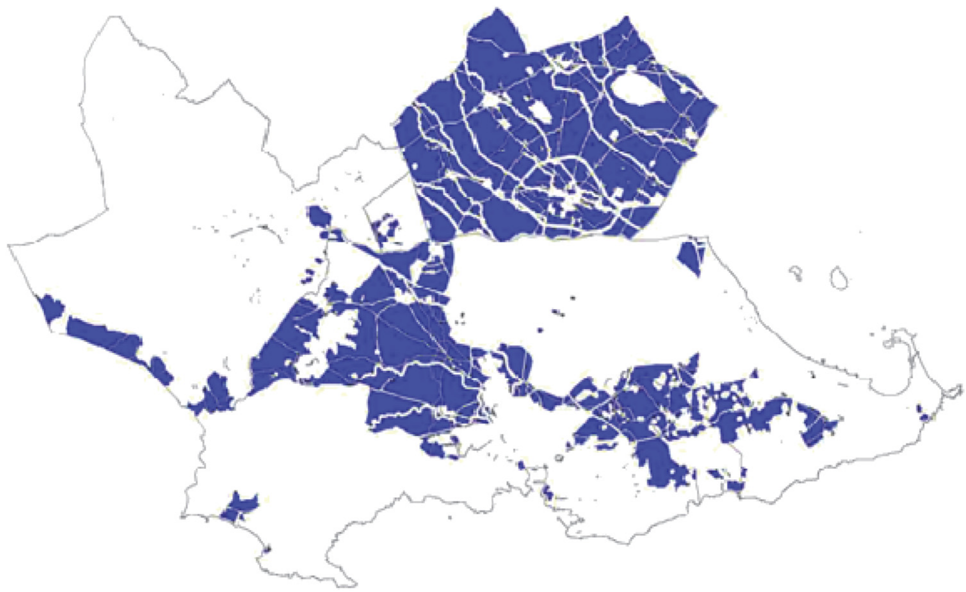

Fig. 7. Suitable areas.

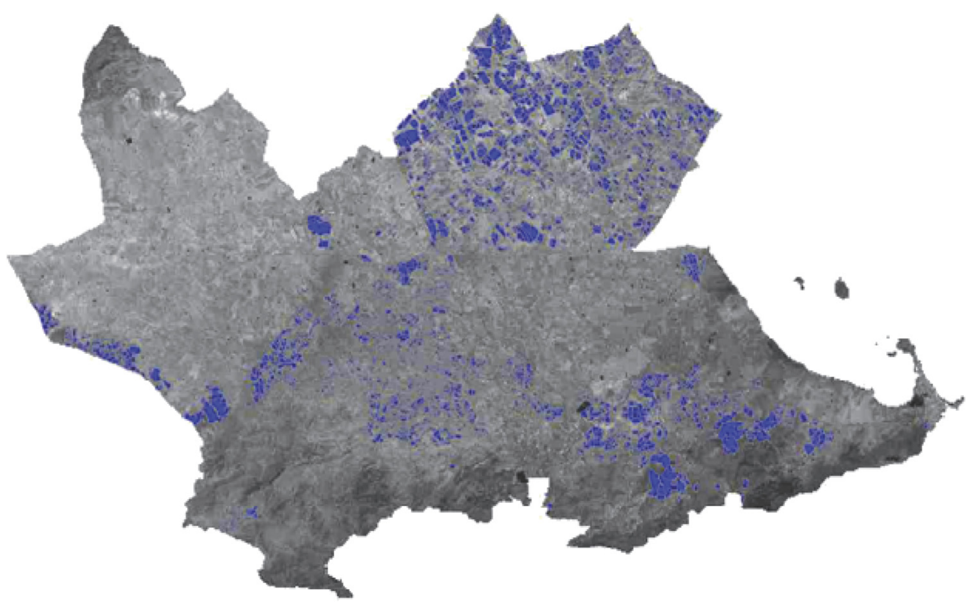

Fig. 8. Suitable areas with cadastral constraints.

which the installation of solar farms is not allowed. The resulting map of plots suitable for the location of solar farms is Fig. 8.

4.2. Phase II: assessing suitable areas

At this point, limiting criteria have been applied, the plots were determined to meet or not meet the restrictions. This second phase will take into account factors that enhance or reduce the carrying capacity of a plot, so a classification of them is obtained according to their suitability to accommodate photovoltaic generation plants.

4.2.1. Definition of criteria and factors

Once the alternatives to evaluate have been defined, they will be evaluated from criteria that influence the decision problem under analysis. There are precedents of the analysis that have already been experimented that an accepted selection of criteria and variables allow to rank the land's degree of capacity. These precedents are tracked and especially investigated for the requirements of each function, to establish appropriate evaluation criteria.

Photovoltaic power plants can be considered as desirable; yet as in any aspect of life they produce adverse effects on society or the environment. Their location can generate a direct benefit for the product not produced but for the infrastructures that are necessary for their functioning (improving access, improving the electrical grid in the area, construction of new substations, new jobs during construction and for subsequent maintenance…). It was decided to follow the criteria established and justified in [29]: Climatic, Location, Geomorphological, and Environmental.

From the above classification, this study will consider the information in the area about the climate. In particular it considers the global radiation and mean annual temperature. By having

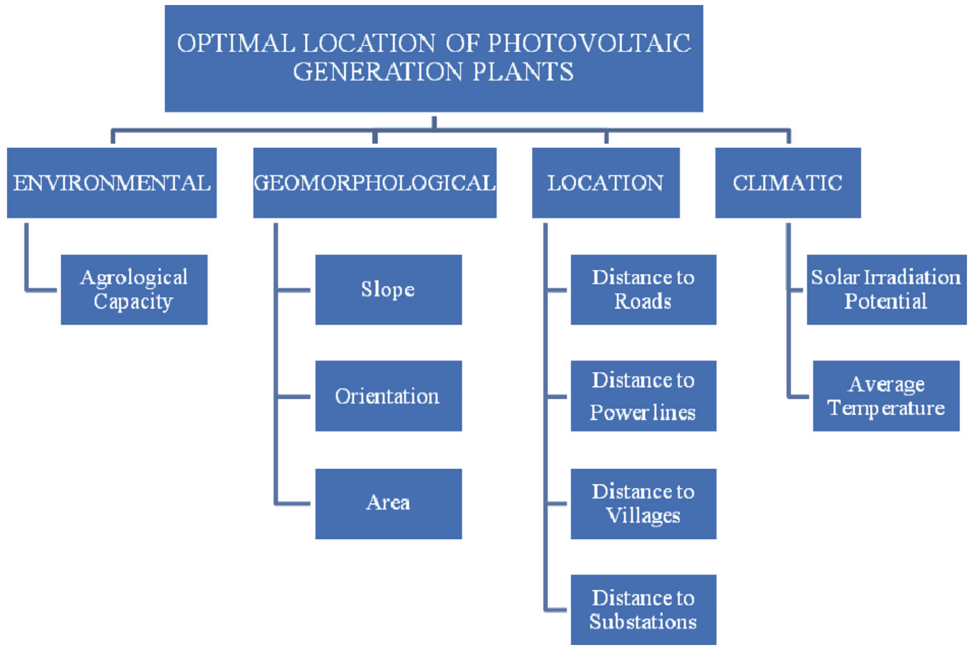

Fig. 9. Hierarchy of criteria and factors.

eliminated all plots that were subject to environmental and administrative constraints, and only taking as a criterion the agrological environmental capacity of the land as the class system of the Soil Conservation Service agrologic U.S., which classes the agrological soil capacity on a scale of I to VIII. It is very important to make a correct assessment of the location as this will very strongly influence the viability or otherwise of the installation. The correct location is given by a good accessibility evaluated by the distance to the main roads in the area, the proximity to the grid to ensure the evacuation of the electricity generated by the proximity to substations and the existence of villages to avoid close losses in the transmission of electricity and thus establishing a system of distributed generation. The last group of factors but not the least defines the geomorphological characteristics of the location. The morphology of the land may limit the host capacity, so areas with high slope should be avoided (it would not be feasible to build on them or it would raise the cost of the installation to have to perform works of raid), the ideal orientation is towards the south and included in the model area of the plot as this will limit the number of modules to install and thus the power of future installation.

Fig. 9 shows the hierarchy of criteria and subcriteria subject to serve as a starting point for the application of the AHP methodology, set out in Section 3, for determining the weight of each of these main criteria and subcriteria.

The many variables that influence the choice of location for the installation of a photovoltaic plant show that it is extremely complex to decide on a location and thus it is necessary to resort to decision support tools.

A literature search was used to determine the relative importance of the criteria, it should be noted that to date the main criterion, which is considered as being more important than others, is the climate.

However, the development of photovoltaic technology, combined with cheaper components means that the criterion of climate no longer feels so important (it should be recalled that radiation and temperature are directly related to the performance of a photovoltaic collector) for the location criterion [29].

Table 3
Weight of criteria and factors.

Criteria	Weight (%)	Factor	Weight of factor (%)
Environmental	5.553	Agrological capacity	**5.553**
Orographical	17.259	Land slope	**11.203**
		Land orientation	**4.815**
		Plot areas	**1.241**
Location	48.625	Distance to villages	**2.849**
		Distance to main roads	**4.291**
		Distance to substations	**8.946**
		Distance to power lines	**32.539**
Climate	28.562	Solar irradiation potential	**23.802**
		Average temperature	**4.7604**

Table 4
Attribute table of the shape with the information of factors and attributes.

Attribute table	
Alternatives	Plots
Cadastral information	Zones and subplots
Factors	Agrological Capacity (AGROL_CLAS) Slope (SLOPE) Orientation (ORIENTATION) Area (PLOT AREA) Distance to main roads (DIST_ROAD) Distance to power lines (DIST_P_LIN) Distance to villages (DIST_NP) Distance to substations (DIST_SUBST) Solar irradiation potential (RADIATION) Average temperature (TEMPERATURE)

In this way location factors are becoming increasingly important, as they seek to create a network of distributed generation that involves the reduction of losses in the transport of the energy generated.

This shift towards the location is also due to the very good and consistent climatic conditions in the region.

For the evaluation of the locations of solar photovoltaic farms, the weights of the criteria to consider will be obtained from the literature [27,29,39,40] which will be supported by an expert in the field of renewable energies. Therefore, the most important criterion will be location, the second will be the climate, the third the land geomorphology, and finally, the environment. By applying the AHP methodology the weights of the factors that influence the decision problem will be obtained. Table 3 presents the results obtained from the application of AHP method, by means of the information obtained from the expert.

The fact that the environmental criterion is the minor may be wrong. This is because the initial study area is not the whole region if they are the resulting plots of phase I. The main objective of environmental criteria is that the impact on the environment is minimal from the point of view of the coexistence of other activities with the use of photovoltaic potential of the region. This will enhance the installation of photovoltaic generation plants in areas with a bad agrological capacity because to do so in excellent land for agriculture would be contrary to the sustainable development sought with the promotion of renewable energy.

4.2.2. Development of the database

In this phase, all data collected would be used to develop the decision model. At this stage of preparation information has been gathered from the study area. Most of the shapes that we were provided with covered the Region of Murcia, so it was necessary to limit them to work only with the areas which were needed to reduce the time required by gvSIG for processing. The remaining layers used or obtained were made or developed during the course of the investigation by the authors. Thematic shapes are showed in Appendix B.

The projection system used was ESPG 23030, corresponding to the UTM zone 30 where the Region of Murcia is. The UTM projection is a transverse cylindrical projection.

To develop the database, the thematic layer that contains the suitable areas to implant solar photovoltaic farms will be split (Fig. 8), in it the surface will be distributed according to the cadastral information (zones, plots and subplots). Starting from this layer and entering the factors that influence the decision in gvSIG, a new thematic layer will be obtained that will show, on the one hand, the alternatives to be evaluated (plots), and on the other hand, the values of the factors seen previously for each of these alternatives. Likewise, the gvSIG software will provide a table (according to the relational database model) called attribute table which will show the thematic information represented in rows and columns so that the rows will constitute the geographical objects. In this case the geographical objects will be the alternatives to evaluate (plots), and the columns (or fields) will define the attributes or thematic variables (cadastral information and factors).

Therefore, the final table will contain the attributes listed in Table 4 in which the denomination of the factors in the gvSIG software is shown in brackets.

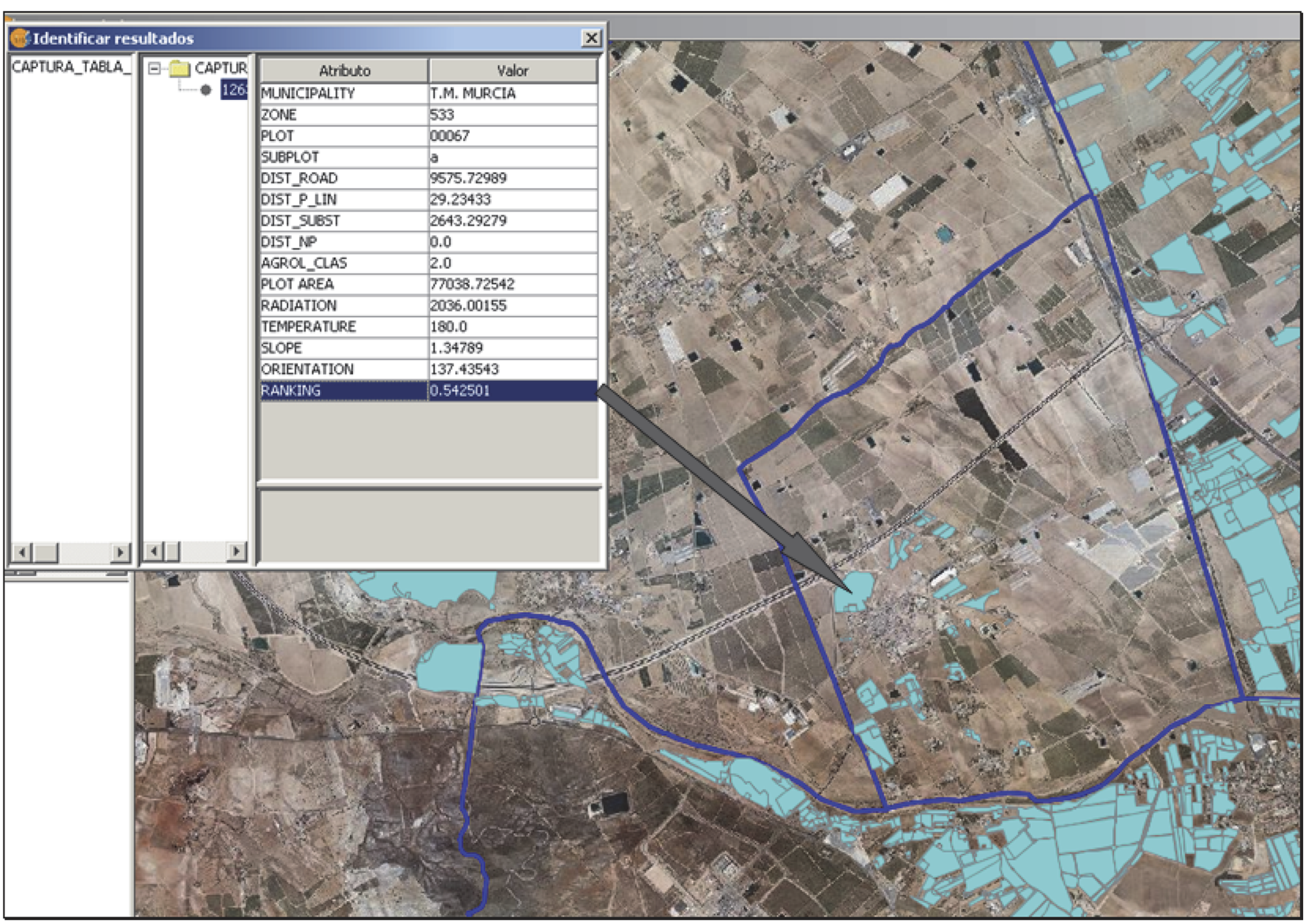

Fig. 10. Cartographic visualization of the ranking of a given plot.

Finally, the relative proximity to all the alternatives was calculated, creating a new field, "R" using the TOPSIS method developed in Section 3.

5. Results and conclusions

Taking as a starting point the data that gvSIG provide and from the calculation tool "Calculadora de Campos" the program carried out the decision process using the TOPSIS method, this process ends with the calculation of the relative proximity to the ideal solution of each alternative that will be called Ranking. For example, Fig. 10 shows the ranking or score for an alternative (plot 67 of zone 533), since the number of alternatives to be analyzed is very high (12,655 plots), one particular area has been chosen as a display example in Fig. 10.

Therefore, the calculation tools of the gvSIG program permit to develop the TOPSIS method entirely and in its last step a ranking is obtained in which the suitable surfaces (valid plots) to implement a solar photovoltaic installation are valued. The above ranking is divided into four intervals so that each interval indicates the capacity (poor, good, very good, excellent) that suitable plots have. The results obtained are shown in Fig. 11 in which the area covered by the study has been highlighted.

The maximum value that is reached (that is the best possible alternative) is 0.54315, this value corresponds to plot 6 of zone 12, which would be the best fitness plot for the implementation of a photovoltaic solar farm. The minimum value of the Ranking is 0.1564 (the worst alternative), it corresponds to plot 230 of zone 16.

Fig. 12 shows the distribution of surfaces based on the ability to host them. Taking the entire surface area studied as a starting point, in the first phase the surface of the area that was valid to implement solar photovoltaic plants (25.50%) was obtained, subsequently a screening process was conducted to exclude plots with less than 1000 m^2 or with buildings inside leaving a valid surface of 147.10 km^2, which corresponds to a percentage of value 13.85%. With this surface classified in cadastral parcels and applying the TOPSIS methodology an assessment or ranking was obtained of the varying carrying capacity of the parcels under consideration, showing that 0.278% of the valid surface is not adequate to implement solar photovoltaic farms; 0.773% has good carrying capacity; 9.591% has very good ability; and finally the remaining 3.206% is excellent.

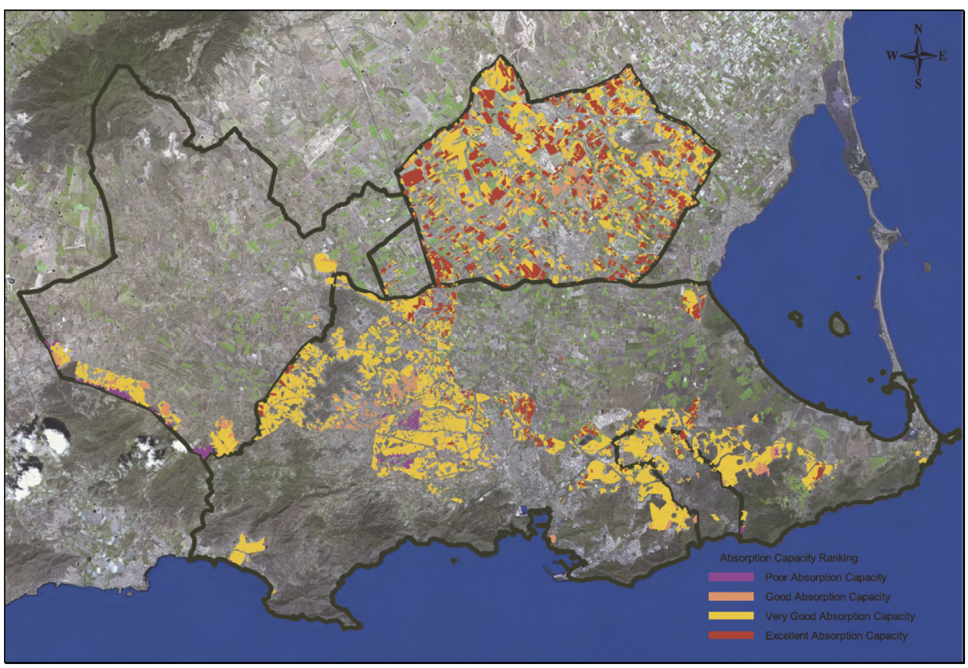

Fig. 11. Absorption ranking.

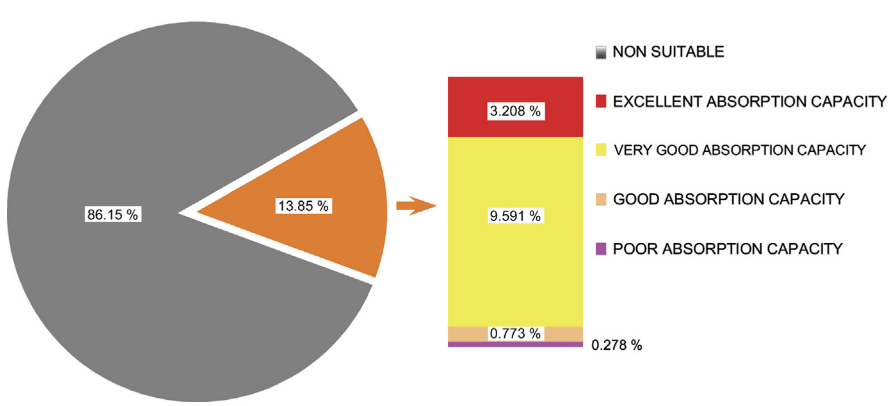

Fig. 12. Valid surface distribution.

Once the combination of GIS–MCDM is made, it is necessary to validate the process and the methodology followed, for this the corresponding sensitivity study should be performed. It is common in the field of GIS that this analysis consists in pixel by pixel validation in order to check if satisfactory results are obtained. For conducting this validation one cadastral plot will be selected at random and it will be exported to a single raster layer. Then the same process of adding the factors to its attribute table will be conducted, reviewing on screen the attributes that are added and those of the defined final layer to check the consistency among them.

The corresponding alternative for plot 67 and subplot *a* (Fig. 10) were randomly selected and proceeding analogously to the process that enabled the creation of the database it was spatially linked to the raster layer that contained such alternative with the layers of main roads, urban lands, power lines and substations. Subsequently it was linked with the agrological capacity layer, the information about the area of the plot was added and, finally the information from the raster layers of slope, orientation, solar radiation and average temperature was added. In this way it could be checked that the attribute table obtained was identical to the row generated for that alternative in the final layer. It was observed that the results were as expected and therefore satisfactory.

With the present study it is found that, due to environmental characteristics, climate, terrain and location, the area of Cartagena is an optimal area to install solar photovoltaic plants because once

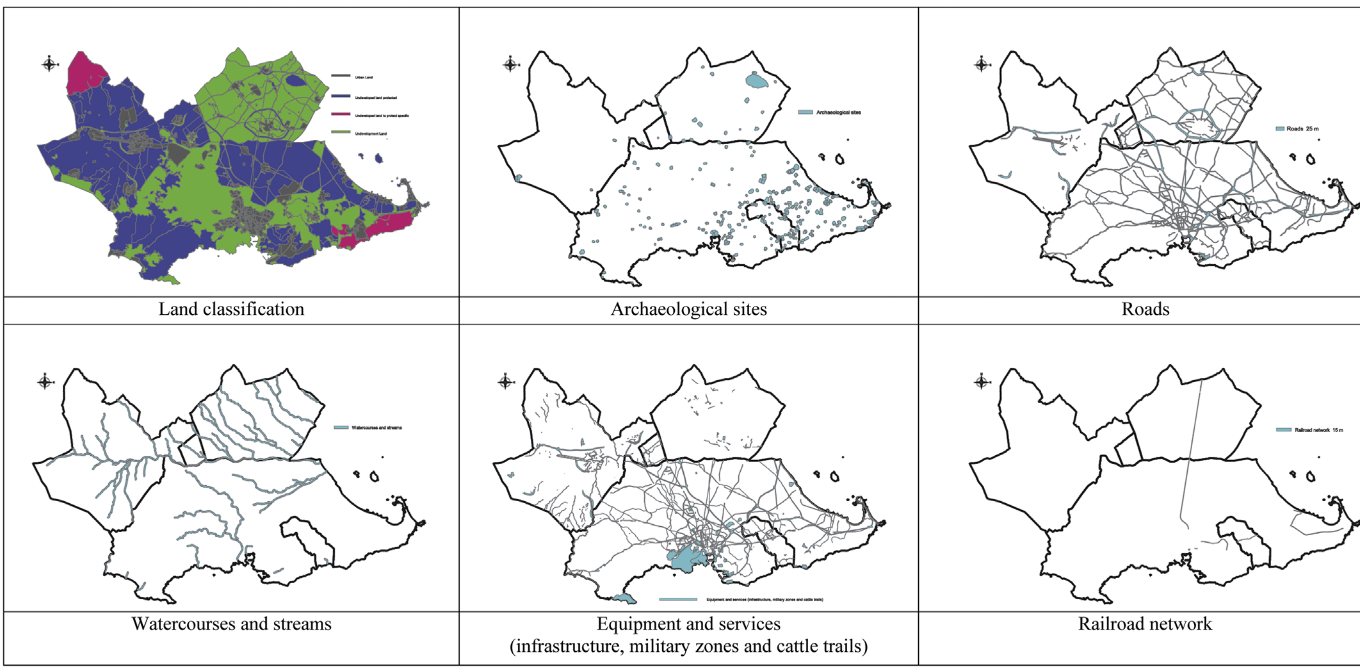

Fig. A1.

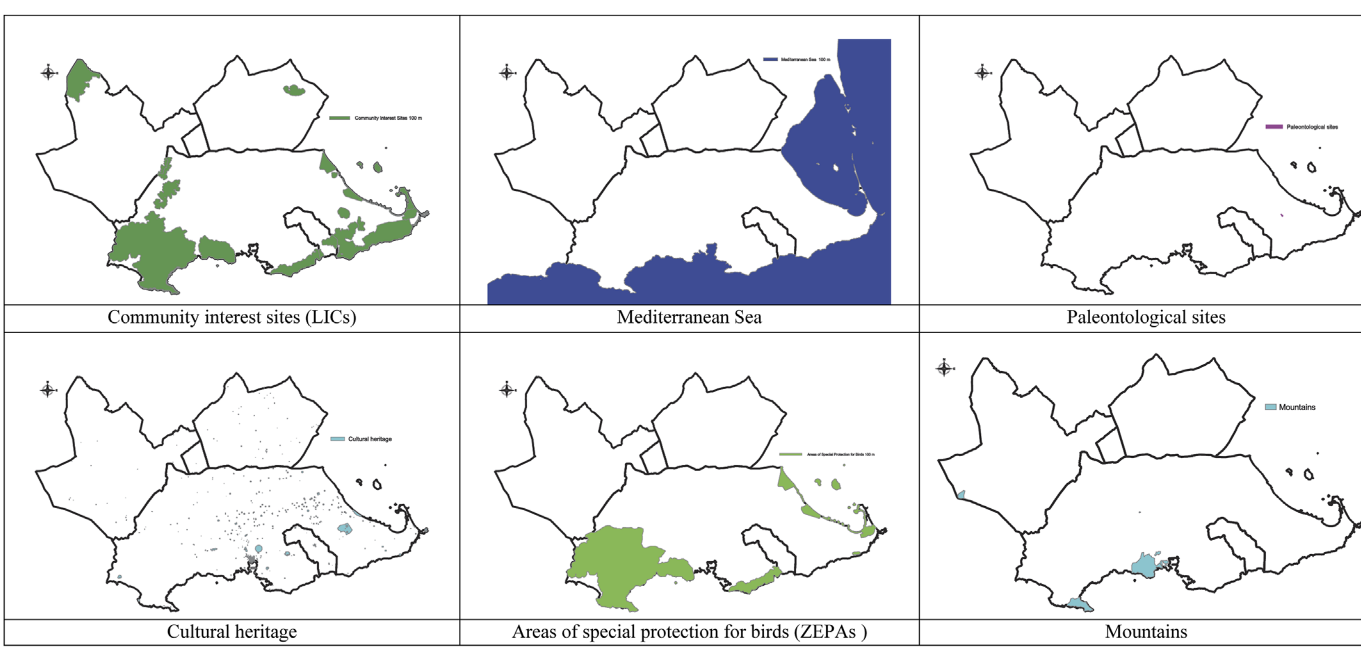

Fig. A2.

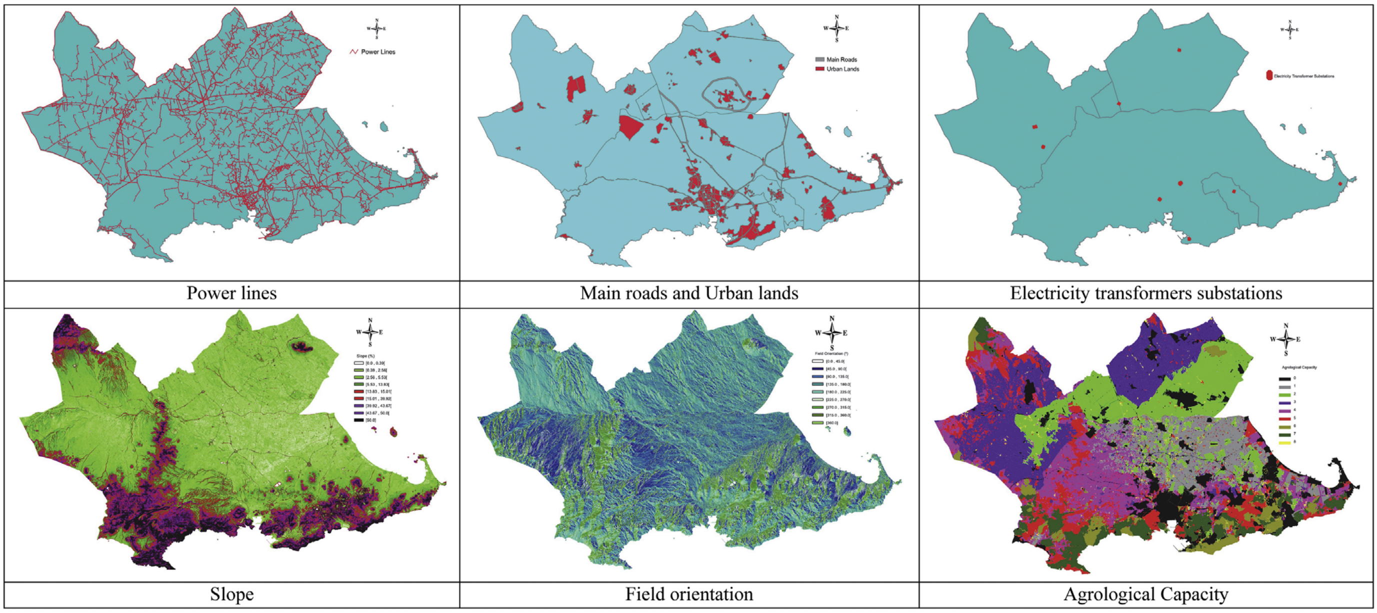

Fig. B1.

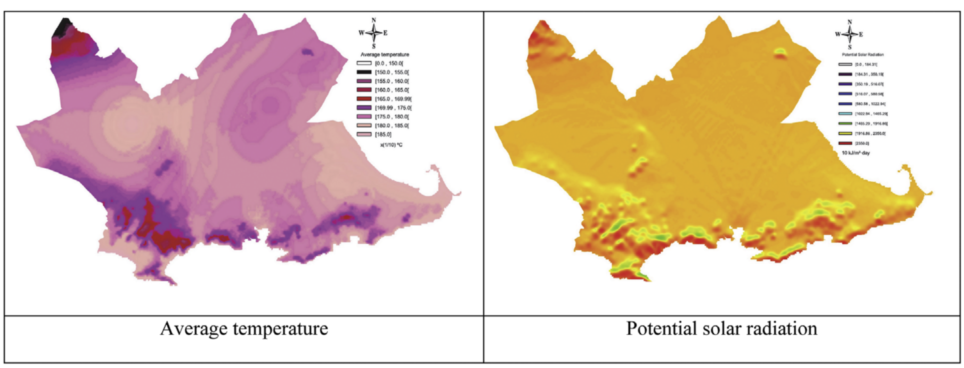

Fig. B2.

all the restrictive or constraints criteria have been considered, the valid surface has a high acceptance rate (very good carrying capacity) to implement solar photovoltaic farms.

Therefore, this study has not only served to assess the ability of the area of Cartagena, it has also demonstrated how it is possible to combine a Geographic Information System with Multi-criteria Decision Making Methods (GIS–MCDM) for use or application in the field of renewable energies, for example when a developer wants to implant a photovoltaic solar farm with specific characteristics (surface to occupy, installed power, etc.), the starting point is to select the best location based on such characteristics. Using GIS–MCDM tools, the difficult task of searching for sites is facilitated so the developer can choose those areas which, from an energy point of view, are optimal and they are also adapted to his or her needs.

However, the analysis conducted has weaknesses that could be strengthened by including linguistic labels in the methodology which could be applied in the definition of certain factors whose nature is qualitative (agrological capacity, orientation. etc.).

Acknowledgment

This work is partially supported by the DGICYT under project TIN2008-06872-C04-04 and TIN 2011-27696-C02-01.

Appendix A. Maps used for each of the limiting criteria

Figs. A1 and A2.

Appendix B. Construction of the thematic shape with added factors

Figs. B1 and B2.

References

[1] Panwar NP, Kaushik SC, Kothari S. Role of renewable energy sources in environmental protection: a review. Renewable and Sustainable Energy Reviews 2011;15:1513–24.
[2] United Nations. Framework convention on climatic change: report of the conference of the parties on its third session. Adoption of the Kyoto Protocol. Kyoto; 1997.
[3] European Commission. Energy for the future: renewable power plants White Book for a Strategy and a Communitarian Plan of Action. COM 1997, 599. Brussels; 1997.
[4] Montes GM, López MMS, Gámez MCR, Ondina AM. An overview of renewable energy in Spain. The small hydro-power case. Renewable and Sustainable Energy Reviews 2005;9:521–34.
[5] García-Cascales MS, Lamata MT, Sánchez-Lozano JM. Evaluation of photovoltaic cells in a multi-criteria decision making process. Annals of Operations Research 2012;199:373–91.
[6] Bhubaneswari P, Iniyan S, Ranko G. A review of solar photovoltaic technologies. Renewable and Sustainable Energy Reviews 2011;15:1625–36.

[7] European Photovoltaic Industry Association (EPIA), Global Market Outlook for Photovoltaic until 2016. 5-42; 2011.
[8] Gómez-López MD, García-Cascales MS, Ruiz Delgado E. Situations and problems of renewable energy in the Region of Murcia, Spain. Renewable and Sustainable Energy Reviews 2010;14:1253–62.
[9] Voogd H. Multicriteria evaluation for urban and regional planning. London: Pion; 1983.
[10] Saaty TL. The analytic hierarchy process: planning, priority setting, resource allocation. New York, NY: McGraw-Hill; 437.
[11] Hwang CL, Yoon K. Multiple attribute decision methods and applications. Berlin Hiedelberg: Springer; 1981.
[12] Ho W. Integrated analytic hierarchy process and its applications—a literature review. European Journal of Operational Reserarch 2008;186:211–28.
[13] Huang JP, Poh KL, Ang BW. Decision analysis in energy and environmental modeling. Energy 1995;20(9):843–55.
[14] Georgopoulou E, Lalas D, Papagiannakis L. A multicriteria decision aid approach for energy planning problems: the case of renewable energy option. European Journal of Operational Research 1997;103:38–54.
[15] Beccali M, Cellura M, Ardente D. Decision making in energy planning: the ELECTRE multicriteria analysis approach compared to a fuzzy-sets methodology. Energy Conversion Management 1998;39(16–18):1869–81.
[16] Haralambopoulos DA, Polatidis H. Renewable energy projects: structuring a multi-criteria group decision-making framework. Renewable energy 2003;28: 961–73.
[17] Pohekar SD, Ramachandran M. Application of multi-criteria decision making to sustainable energy planning—a review. Renewable and Sustainable Energy Reviews 2004;8:365–81.
[18] Terrados J, Almonacid G, Pérez-Higueras P. Proposal for a combined methodology for renewable energy planning. Application to a Spanish region. Renewable and Sustainable Energy Reviews 2009;13:2022–30.
[19] Eunnyeong H, Jinsoo K, Kyung-Jin B. Analysis of the assessment factors for renewable energy dissemination program evaluation using fuzzy AHP. Renewable and Sustainable Energy Reviews 2010;14:2214–20.
[20] Cavallaro F. Fuzzy TOPSIS approach for assessing thermal-energy storage in concentrated solar power (CSP) systems. Applied Energy 2010;87:496–503.
[21] Malczewski J. GIS and multicriteria decision analysis. New York: J. Wiley &Sons; 1999[392p].
[22] Joerin F, Thériault M, Musy A. Using GIS and outranking multicriteria analysis for land-use suitability assessment. International Journal of Geographical Information Science 2001;15:153–74.
[23] Chang NB, Parvathinathan G, Breeden JB. Combining GIS with fuzzy multi-criteria decision-making for landfill siting in a fast-growing urban region. Journal of Environmental Management 2008;87:139–53.
[24] Sadeghi-Niaraki A, Varshosaz M, Kim K, Jung JJ. Real world representation of a road network for route planning in GIS. Expert Systems with Applications 2011;38:11999–2008.
[25] Coutinho-Rodriguez J, Simao A, Henggeler-Antunez C. A GIS-based multi-criteria spatial decisión support system for planning urban infraestructures. Decision Support Systems 2011;51:720–6.
[26] Defne Z, Haas KA, Fritz HM. GIS-based multi-criteria assessment of tidal stream power potential: a case study for Georgia, USA. Renewable and Sustainable Energy Reviews 2011;15:2310–21.
[27] Charabi Y, Gastli A. PV site suitability analysis using GIS-based spatial fuzzy multi-criteria evaluation. Renewable Energy 2011;36:2554–61.
[28] Mari R, Bottai L, Bosillo C, Calastrini F, Gozzini B, Gualtieri G. A GIS-based interactive web decision support system for planning wind farms. Renewable Energy 2011;36:754–63.
[29] Arán-Carrión J, Espín-Estrella A, Aznar-Dols F, Zamorano-Toro M, Rodríguez M, Ramos-Ridao A. Environmental decision-support systems for evaluating the carrying capacity of land areas: optimal site selection for grid-connected photovoltaic power plants. Renewable and Sustainable Energy Reviews 2008;12:2358–80.
[30] Bosque Sendra J, Gómez Delgado M, Moreno Jiménez A, Pozzo F. Hacia un sistema de ayuda a la decisión espacial para la localización de equipamientos. Estudios Geográficos 2000:567–98[Tomo LXI n°241].
[31] Barredo Cano, JI, Gómez Delgado M. Sistemas de Información Geográfica y Evaluación Multicriterio en la ordenación del Territorio. Madrid: RA-MA Editorial; 2005.
[32] Alonso Álvarez, Hidalgo Arquero, Izquierdo Martínez. Empleo del AHP incorporado en SIG para definir el emplazamiento óptimo de equipamientos universitarios. Aplicación a una Biblioteca. Madrid: Universidad Politécnica de Madrid; 2006.
[33] Chen SJ, Hwang CL. Fuzzy multiple attribute decision making: methods and applications. Berlin: Springer-Verlang; 1992.
[34] Zeleny M. Multiple criteria decision making. New York: McGraw-Hill; 1982.
[35] Saaty TL. Group decision making and the AHP. New York: Springer Verlag; 1989.
[36] Loken E. Use of multicriteria decision methods for energy planning problems. Renewable and Sustainable Energy Reviews 2007;11:1584–95.
[37] Yalcin A. GIS-based landslide susceptibility mapping using analytical hierarchy process and bivariante statics in Ardesen (Turkey): comparisons of results and confirmations. CATENA 2008;72:1–12.
[38] Voivontas D, Assimacopoulos D, Mourelatos A. Evaluation of renewable energy potential using GIS decision support system. Renewable Energy 1998;13 (3):333–44.
[39] Janke JR. Multicriteria GIS modeling of wind and solar farms in Colorado. Renewable Energy 2010;35:2228–34.
[40] Jo JH, Otanicar TP. A hierarchical methodology for the mesoscale assessment of building integrated roof solar energy systems. Renewable Energy 2011;36: 2992–3000.